FATIGUE STRENGTH RESTORATION IN CORROSION PITTED 4340 ALLOY STEEL VIA LOW PLASTICITY BURNISHING

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ABSTRACT

Low plasticity burnishing (LPB) is a surface enhancement process with significant economic and physical attributes that make it attractive for component repair/refurbishment applications in aging aircraft. The current work addresses the efficacy of fatigue strength restoration by applying LPB directly to a corroded surface without first removing damaged layers. Compressive residual stresses of the order of material yield strength in quenched and tempered, 38 HRC 4340 steel were achieved via LPB on as-corroded surfaces and sub-surface layers. The total depth of compression was about 1.25 mm (0.05 in.).

Corrosion damage from 100 and 500-hour salt fog exposures reduced the 10^7-cycle fatigue strength respectively by about 25 and 50 percent relative to the as machined uncorroded fatigue strength. LPB applied to the corroded surfaces after superficial cleaning to remove loose corrosion product restored the fatigue strength of the 100-hour exposed material to 110 percent of the as-machined, uncorroded level. Fatigue strength restoration was 85 percent in 500-hour exposed material. Similar degrees of fatigue strength restoration were achieved in the finite life regime as well. Fractography revealed that fatigue failures of salt fog-exposed specimens initiated at corrosion pits. Fatigue failures in LPB treated corroded specimens also initiated at corrosion pits. Nonetheless, fatigue strengths were greatly improved by such treatment.

INTRODUCTION

Despite application of many different corrosion protection schemes, pitting corrosion from the influence of maritime environment commonly occurs in US Naval and Marine Corps aircraft components. This occurs when corrosion protection and prevention systems are consumed or otherwise break down in service.[1] Pitting corrosion is known to significantly reduce fatigue strength and life, especially in the high cycle fatigue regime. Typically, fatigue endurance limits are reduced by pitting to nominally half or less those of uncorroded strength levels[2,3]. From failure analysis experiences, the authors have seen instances where quite superficial pitting as small as 0.025 mm (0.001 in.) has caused initiation of fatigue cracking in aluminum and steel aircraft components. The effects of corrosion and corrosion-induced fatigue reduce useful component life and increase aircraft maintenance costs. Moreover, the downtime for inspections and repair of corrosion damage, during which aircraft are not available for use, significantly impacts military readiness. Estimated annual costs for corrosion inspection and repair of Naval aircraft exceed one billion dollars. These are expected to escalate as military aircraft age further. Currently more than 30% of US military aircraft are over 20 years old. More than 90% will exceed 20 years' age by the year 2015[4].

Common corrosion rework practice in aircraft components is to mechanically remove corroded layers either by hand or by machining followed by a mechanical surface enhancement treatment. The most commonly used treatment is shot peening, which introduces (or re-introduces)

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compressive residual stresses into component surface and subsurface layers. This at least partly compensates for loss of component strength that has resulted from reduction of section size by removal of corrosion-damaged layers. New surface enhancement technologies have recently been developed which are superior to shot peening as regards compressive residual stress magnitudes and depths to which compression can be achieved. Laser shock peening (LSP) has produced marked fatigue life increases in titanium alloy specimens containing deep foreign object damage (FOD)[5,6]. LSP is quite expensive to perform and, for reasons of safety and delicacy of apparatus, is not readily or easily adaptable to aircraft manufacturing and overhaul shop environments. More recently, low plasticity burnishing (LPB) has been demonstrated to provide depths and magnitudes of compressive residual stress comparable to those from LSP yet at far lower cost[7]. LPB can be performed on conventional and CNC machine tools at costs and speeds comparable to those in conventional machining operations.

Recent modeling of fatigue crack growth from corrosion pits in 7075-T6 aluminum alloy specimens indicated that the pits can be considered as semi-elliptical surface cracks of depth on the order of average pit depth for the purpose of predicting fatigue strength degradation[8]. Therefore, if one could induce a layer of compressive stress of sufficient magnitude and depth into a pitted material, one might prevent the formation of fatigue cracking or at least significantly inhibit growth. Residual stress distributions developed via LPB in Ti-6Al-4V[7] and Inconel 718[9] have exceeded 1 mm (0.04 in.) in depth, well beyond the depth of typical corrosion pitting. Indeed, in recent work on 7075-T6[10], the authors demonstrated that typical LPB treatment on surfaces pitted in salt fog environment for 100 and 500 hours restored the fatigue strength to greater than the uncorroded level.

The purpose of the current study was to investigate the effectiveness of LPB in creating a compressive residual stress layer in 4340 steel, 38 HRC and to ascertain the effectiveness of such treatment to restore or improve the fatigue strength of salt fog-pitted specimens relative to the uncorroded level.

EXPERIMENTAL TECHNIQUE

Material

Aircraft quality 4340 steel plate, 13 mm (0.5 in.) thick per AMS 6359F was obtained for the current investigation. The material chemical composition, determined by optical emission spectrograph on an as-received sample of the plate is presented in Table 1 along with reference values per AMS 6359F.

The plate was machined into blanks, 200x33x9mm (8x1.3x3/8 in.), and then was heat-treated by austenitizing, quenching and tempering to 38 HRC. The tensile and 0.2% offset yield strengths, determined per ASTM E 8, were 1160 MPa (168.6 ksi) and 1090 MPa (158.0 ksi) respectively.

Table 1
4340 Steel Plate Composition

Element	Plate Composition (wt.%)	AMS 6359F Limits (wt.%)
C	0.40	0.38-0.43
Mn	0.68	0.60-0.85
P	0.015	0.025 max.
S	0.015	0.025 max.
Si	0.23	0.15-0.35
Cr	0.79	0.70-0.90
Ni	1.70	1.65-2.00
Mo	0.23	0.20-0.30
Cu	--	0.35 max.
Fe	Remainder	Remainder

Low Plasticity Burnishing

All currently available methods of surface enhancement develop a layer of compressive residual stress resulting from mechanical deformation. The methods differ primarily in how the surface is deformed and in the magnitude and form of the resulting residual stress and cold work (plastic deformation) distributions developed in the surface layers.

Conventional air-blast shot peening is routinely applied to a wide variety of aircraft components. High velocity impact of each particle of shot produces a dimple with a region of compression in the center that extends beyond the periphery. Typical compressive residual stress-depth distributions reach a maximum approaching the alloy yield strength, and extend to a depth of 0.05 to 0.5 mm (0.002 to 0.020 in.) The magnitude of compression achieved depends primarily upon the mechanical properties of the alloy. The depth of the compressive layer and the degree of cold working depend upon the peening parameters including shot size, velocity, coverage and impingement angle. Because each shot impacts the surface at a random location, peening for sufficient time to achieve full surface coverage results in many multiple impacts producing a highly cold worked surface layer.[11i]

Conventional shot peening produces from 10% to 50% cold work, much more than from grinding, machining, or other common surface finishing processes.[12] Cold work is cumulative, and repeated applications of shot peening as well as multiples of 100% coverage can produce even more than 50% cold work. Both the depth and degree of cold working increase with peening intensity, with the most severe cold working at the surface. Magnitudes of surface compression often decrease during shot peening of work hardening materials as the yield strength of the surface increases with continued cold working.

The concept of low plasticity burnishing (LPB) originated as a means of producing a layer of compressive residual stress of high magnitude and depth with **minimal** cold work.[13] The process typically involves a single pass of a smooth free rolling spherical ball under a normal force sufficient to plastically deform the surface of the material, thereby creating a compressive layer of residual stress. The process is shown schematically in Figure 1. The ball is supported in a fluid bearing with sufficient pressure to lift the ball off the surface of the retaining spherical socket. The ball is in mechanical contact only with the surface to be burnished and is free to roll on the surface of the work piece.

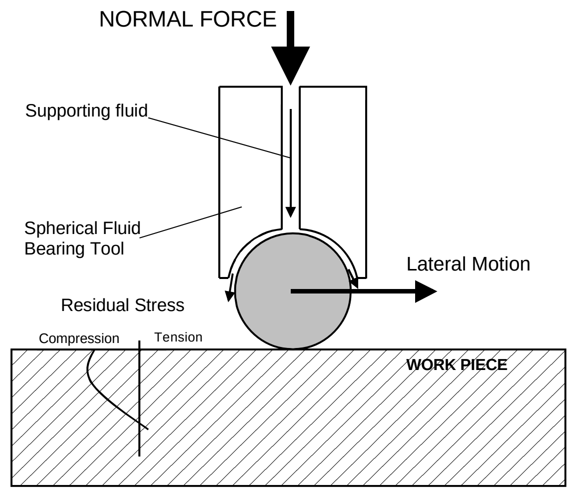


Figure 1 - Low Plasticity Burnishing schematic.

Although the tool designs and hydraulic systems differ, the LPB tooling is similar to “deep rolling” tools using a hydrostatically supported burnishing ball.[14,15,16] The LPB and deep rolling processes differ in the method of use and the level of cold work generated in developing the compressive layer. X-ray diffraction peak broadening and micro-hardness distributions generated by shot peening and deep rolling reveal that deep rolling produces cold work greater than shot peening [14,15,16]. In contrast, LPB typically produces cold work an order of magnitude lower than shot peening [7,9]

Using CNC positioning, the tool path is controlled so that the surface is covered with a series of passes at a separation maintained to achieve maximum compression with minimum cold working. The tool may be moved in any direction along the surface of a complex work piece, as in a typical multi-axis CNC machining operation.

The burnishing ball develops subsurface Hertzian contact stresses in the work piece. These stresses act parallel to the plane of the surface and reach a maximum beneath the surface. With sufficient pressure applied normal to the surface, the subsurface stress exceeds the yield strength of the work piece material, thereby producing deep subsurface compression. The normal force required and the depth at which yielding first occurs depend upon the ball diameter.

The speed of burnishing up to 2.5 m/sec (500 SFPM) has been found to have no effect upon the residual stress distribution produced. This allows application of the process at the highest practical CNC machining speeds.

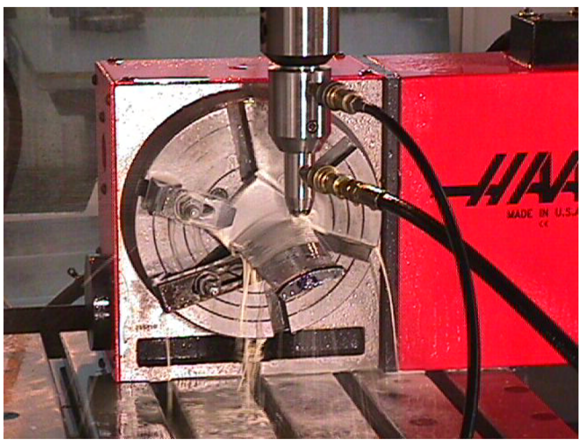


Figure 2 - LPB tool being used in four-axis mode while performing LPB on a compressor blade in a 20 HP vertical CNC mill.

The surface residual stress depends upon the normal force, feed and mechanical properties of both the ball and work piece. Lateral plastic deformation of the surface is necessary to achieve surface compression. Processing parameters have been established empirically. With a poor choice of processing parameters, the surface can be left nearly stress free or even in tension. Empirical optimization has been used successfully to select parameters that leave the surface in compression.

The LPB tool designed to fit a CAT-40 tool holder in a Haas 20 HP vertical CNC mill is shown in four-axis operation in Figure 2. The quill of the machine is not rotated. The swivel links in the hydraulic hose allow exchange of the tool to and from the tool holder so that LPB processing can be incorporated into standard machining sequences in existing CNC machine tools. Injection of the fluid through the quill of the mill is also possible in a suitably equipped machine. With minor modification, the apparatus can be adapted to most horizontal and multi-axis mills, or lathes.

The control apparatus for the hydraulic system provides a constant flow of fluid to support the burnishing ball and a computer controlled feedback system to maintain the desired normal force and fluid pressure. The burnishing force and tool feed can be varied in order to "feather" the residual stress field, thereby providing a smooth transition at the perimeter of the burnished zone or to produce a distribution of residual stress appropriate for a specific application or applied stress field.

The burnishing ball is the only wear prone component of the LPB tooling. High chromium steel, beta-silicon nitride, and sintered tungsten carbide balls, readily available from ball bearing applications, have been used successfully in the current apparatus. The surface finish achievable depends upon the finish of the ball. Bearing balls are commonly available with finishes of grade 25 (25 micro-inch), or better at costs less than cutting tool inserts.

<u>X-ray Diffraction Characterization</u>

Diffraction peak broadening, measured along with the residual stress, allows the amount of damage developed by surface enhancement methods to be accurately assessed. The method of quantifying the degree of cold working of metals, by relating the x-ray diffraction peak broadening to the equivalent true plastic strain, has been described previously.[12] The distribution of cold work as a function of depth into the deformed surface can be expressed in terms of the equivalent true plastic strain. If the degree of cold work is taken to be the equivalent amount of true plastic strain, the degree of cold work is then cumulative and is independent of the mode of deformation. Thus, the subsurface yield strength distribution can then be estimated from true stress-strain curves.[12] The macroscopic residual stress, of primary interest in design and life prediction, is determined in the conventional manner from the shift in the diffraction peak position.[17,18,19]

High Cycle Fatigue Testing

Four-point bending was the HCF testing mode selected to provide maximum sensitivity to the surface condition.[20] Fatigue testing was conducted at room temperature on a Sonntag SF-1U fatigue machine under constant sinusoidal load amplitude at 30 Hz, R=0.1.

A bending fatigue specimen having a trapezoidal cross section was designed especially for the testing of highly compressive surface conditions created by surface enhancement methods. The test specimen provides a nominally 0.5 in. wide by 1-in. long region under uniform applied stress to minimize scatter in fatigue testing. The original gage section thickness of nominally 15 mm (0.375 in.) was chosen to be adequate to support the tensile stresses induced in the back surface of the specimen when a deep highly compressive layer was formed on the test surface. The gage section thickness was then reduced to 0.25 in by milling the backside to insure failure out of the highly compressive surface in four point bending. The HCF samples were finished machined by milling using conventional end milling to simulate the surface conditions including residual stress and cold work that would be present on a machined structural aircraft component manufactured from 4340 steel.

Base line S/N curves were developed for the as-machined condition and the machined condition plus LPB processing. S/N curves were then developed for specimens that had been machined and then exposed to either 100 or 500 hours in the salt fog environment. Half of the specimens given the 100 and 500-hour exposures were then LPB processed. S/N curves were then generated for the as-corroded and corroded plus LPB specimen groups.

Salt Fog Corrosion Exposure

Salt fog corrosion exposures were performed at 35° C per ASTM B117, Standard Practice for Operating Salt Spray (Fog) Apparatus. The fog produced was such that 1.0-2.0 ml/hr of 5 ± 1 mass percent NaCl aqueous solution collected on each 80 cm^2 horizontal surface. The pH of the solution was maintained between 6.5 and 7.2. The salt fog exposure was performed at the Naval Air Depot at Cherry Point using a model TTC600 chamber manufactured by Q-Fog Corporation.

The specimens with the test surface inclined at about 30 degrees from horizontal were exposed in two groups for 100 and 500 hours respectively. Only the specimen gage section areas as machined by end milling-end cutting were exposed. The remaining area of each specimen was protected from exposure using an organic polymer stop off coating. Following salt fog exposures, the coating was removed. The specimens were then soaked and rinsed in tap water followed by a distilled water rinse to remove any salt solution remaining, and then were dried. Specimens exposed for 100 hours received no further cleaning prior to LPB treatment and fatigue testing. Specimens exposed for 500 hours were heavily encrusted with red rust. The rust was removed from these by motorized, light wire brushing prior to LPB treatment and fatigue testing. Wire brushing was performed at 3450 RPM using a 200 mm (8 in.) diameter wire wheel having 0.3 mm (0.012 in) diameter carbon steel wires.

RESULTS AND DISCUSSION

Residual Stress Distributions

Figure 3 shows typical residual stress-depth distributions developed by LPB of the 4340 alloy steel, 38 HRC in this investigation. LPB parameters were developed using Taguchi analysis in a designed experiment to optimize compressive residual stresses and total depth of compression.[21]

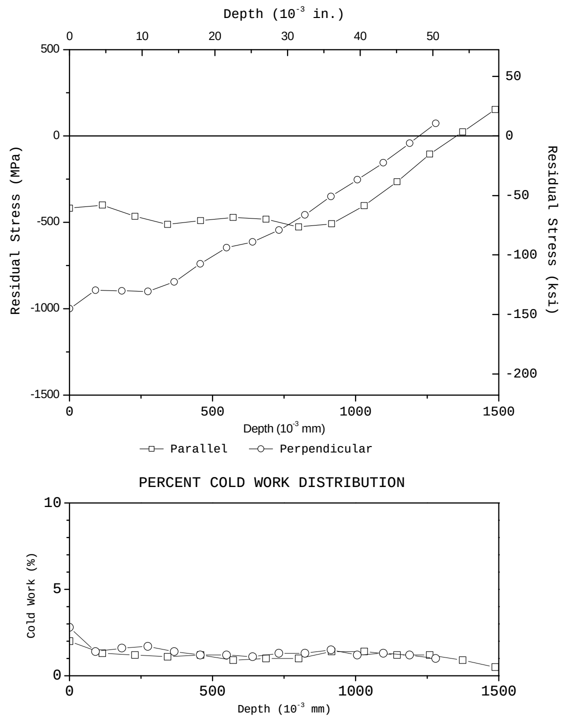


Figure 3 - Residual stress-depth and percent cold work-depth distributions produced by LPB (4340 Steel).

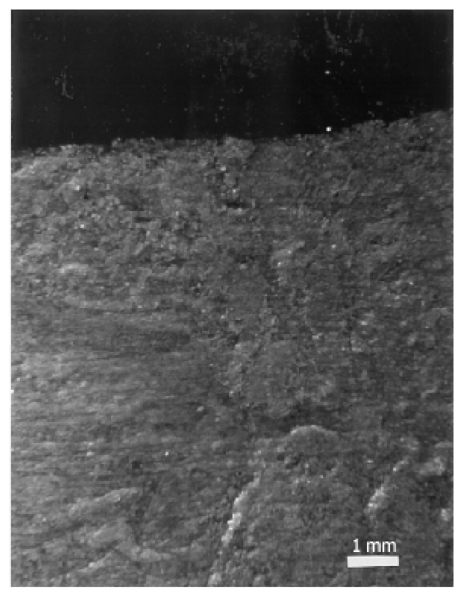
Residual stress-depth results in Figure 3 show differences based on orientation to the direction of ball travel. As has been experienced in other LPB work[9,10] by the authors, greater compression is developed perpendicular to the ball path than parallel to the ball path at the surface and to a considerable depth below. At greater depths the relative compression magnitudes were opposite while the depth of compression was greater parallel to the ball path. These effects occur as a result of the directionality of plastic deformation created in the LPB process. Overall the depth of compression in both directions, 1.2 - 1.4 mm (0.05-0.06 in), was at least three times greater than can normally be achieved via shot peening a material of this hardness at 0.25-0.38 mm (0.010-0.014 in) A intensity[22].

The ball travel direction in the current work was always perpendicular to the specimen longitudinal plane of symmetry. Thus, the component of greater compressive residual stress magnitude was oriented in the same direction as the principal applied stress during bending fatigue testing.

Also shown in Figure 3 is the cold work-depth distribution resulting from LPB. As may be seen, the amount of cold work was generally small (< 3%) as is desirable in LPB. The maximum cold work at the surface was only very slighter greater than at any subsurface depth.

Corrosion Damage

100-hr Salt Fog



500-hr Salt Fog

Figure 4 - Typical surface appearance after salt fog exposure.

Optical examination of salt fog corroded surfaces revealed generally that only slight general corrosion and pitting, typically 0.05-0.10 mm (0.002-0.004 in) deep, had occurred after 100 hour exposure. After 500 hour exposure, severe general corrosion and pitting, typically 0.12-0.25 mm (0.005-0.010 in) deep, had occurred. Figure 4 shows macrophotographs of typical surfaces after 100 and 500 hour salt fog exposures.

Surface roughness data presented in Table 2 give indications of the surface degradation from salt fog exposure as well as the improvement thereof from LPB. As may be seen, corrosion seriously degraded the machined surfaces with roughness increasing with exposure time. LPB of 100 hour-exposed surfaces improved overall roughness to a level superior to the starting as-machined surfaces. LPB improved 500 hour exposed surfaces; however, these surfaces remained much rougher than in the as machined condition.

Table 2 Surface Roughness Results

Specimen Surface Condition	**Average Roughness** µm (µ–in)
As machined	0.6 (26)
Machined + LPB	0.12 (5)
100 hr salt fog (SF)	2.7 (107)
100-hr. SF + LPB	0.3 (13)
500-hr. SF + wire brush	9.6 (380)
500-hr. SF + wire brush + LPB	2.5 (100)

<u>High Cycle Fatigue Results</u>

Figure 5 shows fatigue S-N curves generated from specimens having six different surface conditions. These were:

As machined (end milling-end cutting)
Machined + LPB
Machined + 100-hr. salt fog exposure
Machined + 100-hr. salt fog + LPB
Machined + 500-hr. salt fog exposure
Machined + 500-hr. salt fog + LPB

For convenience in visualizing fatigue strength differences, maximum stress values at 10^7 cycles for each surface condition are presented in bar chart form in Figure 6.

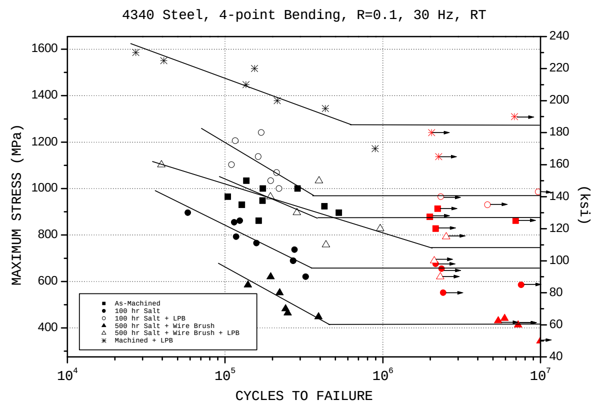


Figure 5 - High cycle fatigue S/N Data

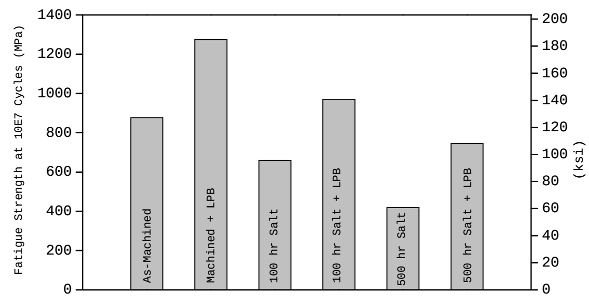


Figure 6 - Long life fatigue strength (4340 Steel).

As seen in Figures 4 and 5, LPB treatment increased long-life fatigue strength approximately 30 percent relative to the as machined condition at all cyclic lives. This increase is attributed to delay in crack initiation and retardation of fatigue crack growth by the residual compressive stresses induced in surface and subsurface layers by LPB.

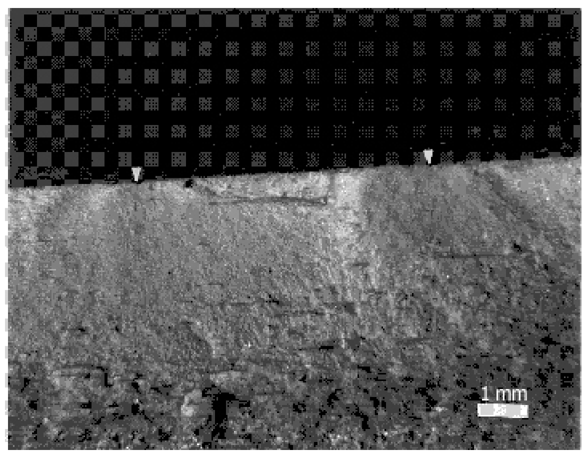
As would be expected, corrosion on machined surfaces reduced fatigue resistance. As revealed in Figure 5, salt fog corrosion exposures greatly reduced fatigue strength relative to the machined condition at all cyclic lives. Fatigue strength reductions relative to the as machined condition of 30-35 percent and 45-55% were observed in specimens exposed for 100 and 500-hrs. respectively.

LPB treatment after corrosion exposure greatly improved the fatigue strength of corroded surfaces. For the 100-hr. exposed condition, the improvement was nearly 50 percent, giving fatigue strength at 10^7 cycles more than 10 percent greater than for the original machined condition. The 60 percent fatigue strength improvement by LPB for the 500-hr. exposed condition was also quite marked; however , the strength level after LPB remained 25 percent less than for the original as machined condition. Apparently, compressive stresses from LPB tend to delay and retard crack initiation and progression in corrosion damaged; however, not to the full extent exhibited by LPB treatment on a relatively undamaged, machined surface.

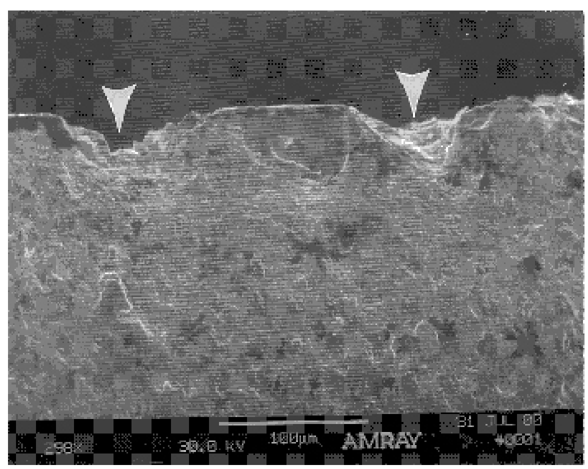
Not included in the scope of this investigation, but certainly deemed worthy of further exploration, are three additional issues. The first is the effect of LPB on fatigue strength restoration after full or partial removal of corrosion damage. The second is the effect of LPB prior to exposure on corrosion damage sustained, and the third is the issue of fatigue strength restoration after corrosion of an LPB treated surface.

Fractography

Fatigue fractures in all specimens were examined optically at magnifications to 40x to ascertain fatigue origin locations relative to processed surface areas and to determine if any extraneous features or anomalies had influenced failure. In general, all fatigue failures occurred within specimen gage sections and within representatively processed surface areas. All fatigue origins occurred at specimen surfaces insofar as could be observed optically. This is not surprising because the applied stress bias of the four-point bending, R = 0.1 testing mode would inherently favor surface fatigue origins. All machined and LPB treated machined specimens exhibited single fatigue crack origins. Multiple fatigue initiation sites were observed generally in salt fog corroded specimens and LPB treated corroded specimens. These sites were at corrosion pits even in the case of the LPB treated specimens despite their significantly greater fatigue strengths relative to as corroded untreated specimens. This was in contrast to observations made in a previous similar investigation on 7075-T6 aluminum alloy[10] wherein fatigue origins in LPB treated specimens occurred subsurface remote from corrosion pits having the same order of depths as those observed in the current investigation. In that previous work, full rather than partial restoration of fatigue strength from LPB after both 100 and 500-hr. exposures was achieved. From this it is apparent that not all degrees of corrosion damage in steel can be fully mitigated by LPB notwithstanding that pits were only 20 percent or less than the LPB depth of compression.



(a) Optical



(b) SEM

Figure 7 - Fatigue origins in two LPB treated, 100 hr. salt fog exposed specimens.

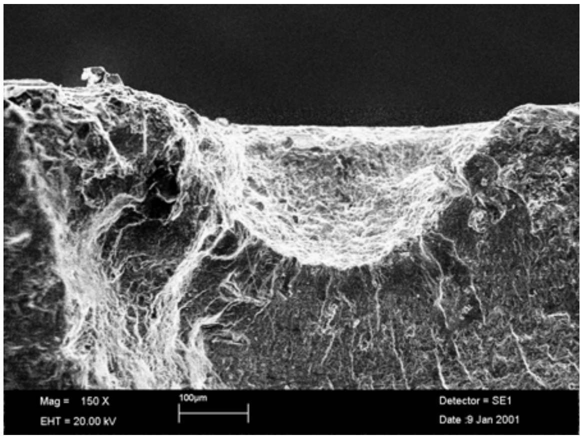


Figure 8 - Multiple microscopic fatigue origins from corrosion pit in LPB treated, 500 hr. salt fog exposed specimen.

A few specimens were selected for higher magnification fractographic observation via scanning electron microscopy (SEM). As-machined and LPB treated machined specimens exhibited single fatigue origins at specimen surfaces, confirming optical observations. No anomalous surface or subsurface features were noted. Also confirming optical observations, fatigue origins in as-corroded and LPB treated corroded specimens were from corrosion pits. Figure 7 is an exemplary micrograph of fatigue origins in an LPB treated, 100 hour exposed specimen. Corrosion pits were observed to be approximately hemispherical in shape. Figure 8 is an exemplary micrograph showing multiple fatigue initiation sites at the boundary of a pit in an LPB treated, 500-hr. exposed specimen.

SUMMARY AND CONCLUSIONS

Low plasticity burnishing was successfully applied to produce significant compressive residual stresses in 4340 steel, 38 HRC from the surface to about 1.25 mm (0.050 in) deep. The magnitude of compression exceeds that which can be achieved via conventional shot peening while the LPB depth of compression is two to three times greater.

Salt fog exposures produced general corrosion and pitting to depths up to 0.25 mm (0.010 in). This resulted in fatigue strength degradation up to 60 percent relative to the as machined, uncorroded surface condition.

LPB treatment on 100-hr salt fog corroded surfaces, without removal of pitted material or corrosion products restored the fatigue strength to greater than that from the as machined uncorroded condition. LPB treatment on 500-hr. salt fog corroded surfaces, after removal of only the loose corrosion product, restored fatigue strength to within 75 percent of the as-machined uncorroded strength.

ACKNOWLEDGMENT

Appreciation is expressed for partial support of this work provided by the Materials Engineering Division, Naval Aviation Depot, Cherry Point, NC during employment there of one of the authors (JTC). Direct assistance with specimen preparation and testing provided by personnel at Cherry Point (James Whitfield) and Lambda Research (Douglas Hornbach and Perry Mason) is further acknowledged. The authors also thank Perry Mason and Kimberley Bellamy of Lambda Research for assistance in manuscript preparation.

REFERENCES

1. J.T. Cammett, "Analysis of H-46 Rotor Head Component Fatigue Cracking", Proc. 42nd Int'l SAMPE Symposium, 1997.
2. ASM Handbook, Vol. 19, Fatigue and Fracture, S.R. Lampman, ed., ASM International, Metals Park, OH, 1996, pp. 596-597.
3. N.E. Dowling, Mechanical Behavior of Materials, Prentice Hall, NJ, 1993, p. 365.
4. V.S. Agarwala, "Corrosion and Aging Aircraft Concerns", Presentation at 11th Annual Aeromat Conference, Bellevue, WA, June 26-29, 2000.
5. A.H. Clauer, "Laser Shock Peening for Fatigue Resistance ", Surface Performance of Titanium, J.K. Gregory et al. Eds., TMS, Warrendale, PA, 1996, pp. 217-230.

6. 6. P.R, Smith, M.J. Shepard et al., "Effect of Laser Shock Processing (LSP) Power Density and Shot Repetition on Residual Stress Distributions and % Cold Work in Ti-6Al-4V", Proc. 5th National Turbine Engine HCF Conference, 2000.
7. P.S. Prevey "The Effect of Low Plasticity Burnishing (LPB) on the HCF Performance and FOD Resistance of Ti-6Al-4V", Proc. 6th National Turbine Engine HCF Conference, Jacksonville, FL, Mar 5-8, 2001.
8. K.K. Sankaran, R. Perez and K.V. Jata, "Pitting Corrosion and Fatigue Behavior of Aluminum Alloy 7075-T6", Advanced Materials and Processes, ASM Int'l., August, 2000, pp. 53-54.
9. P.S. Prevey, "The Effect of Cold Work on the Thermal Stability of Residual Compression in Surface Enhanced IN718", Proc. 20th ASM Materials Solutions Conference & Exposition, St, Louis, MO, October 10-12, 2000.
10. P.S. Prevey and J.T. Cammett, "Low Cost Corrosion Damage Mitigation and Improved Fatigue Performance of Low Plasticity Burnished 7075-T6"' Presentation at 4th International Aircraft Corrosion Workshop, Solomons, MD, August 22-25, 2000, Submitted for publication to Journal of Materials Engineering Performance.
11. D. Lombardo and P. Bailey, "The Reality of Shot Peen Coverage", 6th International Conference on Shot Peening, J. Champaigne ed., 1996, pp. 493-504.
12. P.S. Prevey, Residual Stress in Design, Process & Material Selection, ASM, Metals Park, OH 1987, pp. 11-19.
13. U.S. Patent 5,826,453, October, 1998 (Other patents pending).
14. W. Zinn and B. Scholtes, "Mechanical Surface Treatments of Lightweight Materials – Effects on Fatigue Strength and Near-Surface Microstructures", Journal of Materials Engineering and Performance, V. 8(2), April, 1999, pp. 145-151.
15. I. Altenberger et al., "Cyclic Deformation and Near Surface Microstructures of Shot Peened or Deep Rolled Austenitic Stainless Steel AISI 304", Materials Science and Engineering, A264, 1998, pp. 1-16.
16. A. Dreschler et al., "Mechanical Surface Treatments of Ti-10V-2Fe-3Al for Improved Fatigue Resistance", Material Science and Engineering, A243, 1998, pp. 217-220.
17. P.S. Prevey, Metals Handbook, V. 10, ASM, Metals Park, OH, 1986, pp. 380-392.
18. Residual Stress Measurement by XRD, SAE J784a, M.E. Hilley ed., SAE, Warrendale, PA, 1971.
19. I.C. Noyen and J.B. Cohen, Residual Stress Measurement by Diffraction and Interpretation, Springer-Verlag, NY, 1987.
20. P.S. Prevey and W.P. Koster, "Effect of Surface Integrity on Fatigue of Aerospace Alloys at Elevated Temperatures", ASTM STP 561, ASTM, Phil., PA, pp. 522-531.
21. Lambda Research, Inc., Unpublished data.
22. H.O. Fuchs and J.J. Daly, "Mechanical Production of Self Stresses", Advances in Surface Treatments, vol. 4, Residual Stresses, p. 81, Pergamon, 1987.